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Cavitation Effects on the Stability of a Submerged Journal Bearing

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A computational procedure for the mechanism of shear between the liquid sublayer and air cavity in the cavitation zone of a submerged journal bearing is presented here. Using the mass conservation principle, Elrod's universal equation is modified to take into consideration the shear of the air cavity in the cavitation region. Results of steady state and transient response for the submerged journal bearing using the present approach are compared with the universal equation based on the striated flow in the cavitation region. At steady state, the angular extent of cavitation region predicted by the present approach is higher than that predicted by Elrod's model and the limit cycle journal transient response using the present approach predicts higher eccentricity ratios.

Keywords Air cavity, Lubricant layer, Mass conservation principle, Submerged journal bearing

A large wealth of literature is reported on the theoretical modeling and experimental works on the cavitation of journal bearings. The fluid film in the converging–diverging geometry of journal bearing cavitates within the divergent region. As the fluid film tries to occupy the clearance space with increasing volume in the divergent region, the pressure drops below the saturation pressure in a submerged journal bearing resulting in

an appearance of air/gas cavities. Groper and Etsion (2001) theoretically investigated the (1) shear of cavity bubble by the lubricant flow attached to the journal surface and (2) diffusion of the dissolved gases into and out of lubricant. Their results indicate that the mechanism of diffusion of gases is inadequate to explain the experimental observation of cavity pressures while the mechanism of shear of gas cavity accurately predicts the cavity shape compared to cavity pressures. Experimental investigations (Etsion and Ludwig, 1982; Braun and Hendricks, 1984) in the cavitation region of submerged journal bearings also reveal the existence of cavity pressures in the range of 105–130 kPa absolute. In general, theoretical works on the cavitation in bearings assume the pressure in the cavity to be constant and often does not emphasize experimental observations of pressure build-up in the cavitation zone of a submerged journal bearing.

Dowson and Taylor (1974) made an excellent review of various boundary conditions that are applicable to the cavitation region. Some of the prominent numerical implementations of the cavitation modeling of journal bearings (Elrod, 1981; Brewe, 1986; Vijayaraghavan and Keith, 1989; Vijayaraghavan and Brewe, 1992) based on the mass conservation principles are in wide use to predict the exact boundaries of the fluid–film and cavity interface. However, these numerical models are based on the assumption of constant cavity pressure (JFO theory). Elrod (1981) developed a universal equation based on the striated flow in the cavitation zone of a journal bearing. The Elrod algorithm uses a switching function to predict the cavitation and full film regions based on the conservation of mass. Heshmat's (1991) experimental observations reveal three modes of cavitation, one possibility being the existence of a sublayer attached to the moving journal surface.

The present study attempts to investigate shear effect of air cavity (Groper and Etsion, 2001) by the swept-away lubricant sublayer in the cavitation region. Based on mass conservation principles, a universal equation is developed, similar to Elrod's

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(Elrod, 1981) algorithm. The fractional film content and the nondimensional pressure in the full film region are evaluated using a robust computational technique (Vijayaraghavan and Keith, 1989; Vijayaraghavan and Brewe, 1992).

ANALYSIS

Figure 1 shows the geometry of a submerged journal bearing. It is assumed that all the lubricant in the cavitation region is swept away by the journal surface. Also, there is no lubricant flow along the axial direction in the cavitation region. Neglecting the transition zones from full film rupture to the sublayer film in both radial and circumferential directions, as well as neglecting the surface tension effects, the momentum equations for the air cavity and sublayer attached to the rotating journal are (Groper and Etsion, 2001):

$$\eta_k \frac{\partial^2 u_k}{\partial y^2} = \frac{\partial p_c}{R \partial \alpha}, \quad k = l, g \quad [1]$$

or

$$\eta_l \frac{\partial^2 u_l}{\partial y^2} = \eta_g \frac{\partial^2 u_g}{\partial y^2} \quad [2]$$

The velocity boundary conditions at the bearing surface, journal surface, and the liquid and gas interface are:

$$\begin{aligned} u_l &= U \quad \text{at } y = 0, h_i \quad \text{and} \quad u_g = U \quad \text{at } y = h_i; \\ u_g &= 0 \quad \text{at } y = h \end{aligned} \quad [3]$$

The continuity of shear stress at the air cavity and sublayer interface is (Groper and Etsion, 2001):

$$\eta_l \left. \frac{\partial u_l}{\partial y} \right|_{y=h_i} = \eta_g \left. \frac{\partial u_g}{\partial y} \right|_{y=h_i} \quad [4]$$

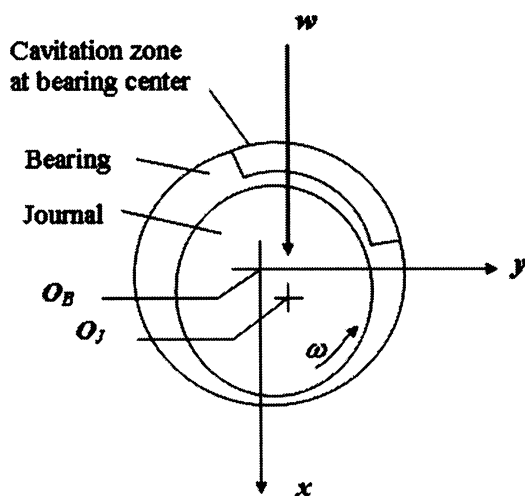


FIGURE 1

Geometry of submerged journal bearing.

The velocity of sublayer in the cavitation region is obtained by integration of Equation [2] with the conditions given in Equations [3]–[4]; that is:

$$u_l = \frac{\eta_g}{\eta_l} u_g + \left(1 - \frac{\eta_g}{\eta_l}\right) U \quad [5]$$

The mass flow rate of liquid in the circumferential directions is:

$$q_l = \rho_l \int_0^{h_i} u_l dy \quad [6]$$

Substituting Equation (5) into Equation (6) results in:

$$q_l = \rho_l \int_0^{h_i} \left(1 - \frac{\eta_g}{\eta_l}\right) U dy, \quad \text{since } \rho_l \int_0^{h_i} \frac{\eta_g}{\eta_l} u_g dy = 0 \quad [7]$$

Equation (7) is simplified to:

$$q_l = \rho_l \left(1 - \frac{\eta_g}{\eta_l}\right) U h \theta \quad [8]$$

where, θ is defined as a fractional film thickness $\frac{h_i}{h}$, and h_i is the thickness of film in the cavitation region ($\theta < 1$), if the entire fluid film were to adhere to the journal surface. In the full film region, θ is defined as the ratio of densities ($\theta > 1$), which is the same as that of Elrod's model.

The modified Elrod equation (Elrod, 1981) in the cavitation region is given as:

$$\frac{\partial}{\partial t}(\rho_l h_i) + \frac{\partial}{R \partial \alpha} \left\{ \rho_l \left[1 - \frac{\eta_g}{\eta_l}\right] U h \theta \right\} = 0 \quad [9]$$

The modified, nondimensional universal equation which conserves mass, and is applicable for both full film and cavitated regions (Brewe, 1986) under dynamic conditions for a laminar and compressible fluid flow, is:

$$\begin{aligned} \frac{\partial}{\partial T}(\theta H) + \frac{\partial}{\partial \alpha} \left\{ \frac{\theta H}{k} - \frac{\beta_g H^3}{12} \frac{\partial \theta}{\partial \alpha} \right\} \\ + \left(\frac{R}{L}\right)^2 \frac{\partial}{\partial Z} \left\{ -\frac{\beta_g H^3}{12} \frac{\partial \theta}{\partial Z} \right\} = 0 \end{aligned} \quad [10]$$

where, k is defined as the fluid film velocity factor

$$k = \begin{cases} 2 & \text{in the full film region } (\theta > 1) \\ \left(1 - \frac{\eta_g}{\eta_l}\right)^{-1} & \text{in the cavitation region } (\theta < 1) \end{cases} \quad [11]$$

and g is a switch function introduced to remove the pressure gradient terms in the cavitated regions (it takes value of 0 for $\theta < 1$).

The modified Elrod universal equation (Equation (10)) is solved using the numerical procedure involving Newton Iteration and Approximate Factorization (AF) scheme (Vijayaraghavan and Brewe, 1992).

In the present work, the modified shear flow terms in Equation (10) are expressed analogously as in the algorithm of Vijayaraghavan and Brewe (1992); that is,

$$\begin{aligned} \frac{\partial}{\partial \alpha} \left\{ \frac{\theta H}{k} \right\}_{i,j} &= \frac{g_u}{2\Delta\alpha} \left\{ \left(\frac{\theta H}{k} \right)_{i,j+1} - \left(\frac{\theta H}{k} \right)_{i,j-1} \right\} \\ &+ \frac{|g_u|}{2\Delta\alpha} \left\{ (g_{i,j+\frac{1}{2}} - 1) \left(\frac{\theta H}{k} \right)_{i,j+1} + (2 - g_{i,j+\frac{1}{2}} - g_{i,j-\frac{1}{2}}) \right. \\ &\times \left. \left(\frac{\theta H}{k} \right)_{i,j} + (g_{i,j-\frac{1}{2}} - 1) \left(\frac{\theta H}{k} \right)_{i,j-1} \right\} \end{aligned} \quad [12]$$

where g_u is a switch function for surface velocity. In Equation (12), $g_u = 1$, considering the positive net surface velocity $U = 1 - 2\dot{\phi}$ and $g_u = -1$ for $U < 0$.

When $g_{i,j-1} = 1$, $g_{i,j} = 1$, and $g_{i,j+1} = 1$, then θ can be neglected in the full film region as $\frac{\partial}{\partial \alpha} \left\{ \frac{\theta H}{k} \right\} = \frac{\partial}{\partial \alpha} \left\{ \frac{H}{k} \right\}$.

EQUATIONS OF JOURNAL MOTION

The equations of motion in nondimensional form for a two-degree of freedom rotor bearing system, considering the hydrodynamic and external forces, are:

$$\begin{cases} M \frac{d^2 X}{dT^2} = -\frac{F_x}{W} + [1 + a_p \sin(\Omega T)] \\ M \frac{d^2 Y}{dT^2} = -\frac{F_y}{W} \end{cases} \quad [13]$$

where, the fluid film forces are

$$\begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = - \int \int P \begin{Bmatrix} \cos \alpha \\ \sin \alpha \end{Bmatrix} d\alpha dZ \quad [14]$$

A sinusoidal load variation is considered according to the relation (Vijayaraghavan and Brewe, 1992):

$$w = w_b \{1 + a_p \sin(\Omega T)\} \quad [15]$$

RESULTS AND DISCUSSION

In order to examine the validity of the present approach with those already well known in the literature, numerical examples of submerged journal bearing are considered. The operating conditions for the submerged journal bearing are shown in Table 1 under steady-state condition.

TABLE 1

Bearing Data for a Submerged Journal Bearing
(Vijayaraghavan and Keith, 1989)

L/D	4/3
β	40
ε	0.2 and 0.8
P_c	-1.0
P_a	0.0

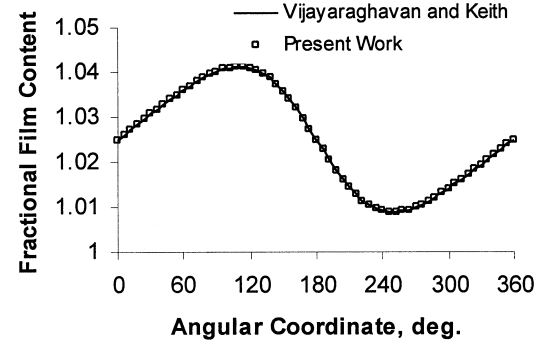
TABLE 2

Bearing Operating Conditions for a Submerged Journal Bearing (Vijayaraghavan and Brewe, 1992)

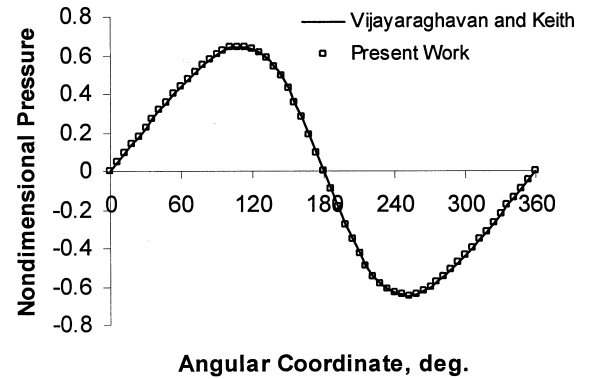
L/D	0.562		K	1.72×10^8	N/m ²
R	0.1	m	η_g	2×10^{-5}	Pa·s
C	80	μm	η_l	0.015	Pa·s
p_a	1.0133×10^5	N/m ²	N	600	rpm
p_c	0.0	N/m ²	Ω	0.25 and 3.0	
M	5.0		X_o	0.65	
a_p	1.0		Y_o	0.0	
w_b	40×10^3	N			

Table 2 gives the bearing data and operating conditions for the stability analysis of submerged bearing under periodic loading. The purpose of this article is to compare the results to those obtained by considering striated flow in the cavitation region.

The steady-state computations were performed for the submerged bearing data studied in Vijayaraghavan and Keith (1989).



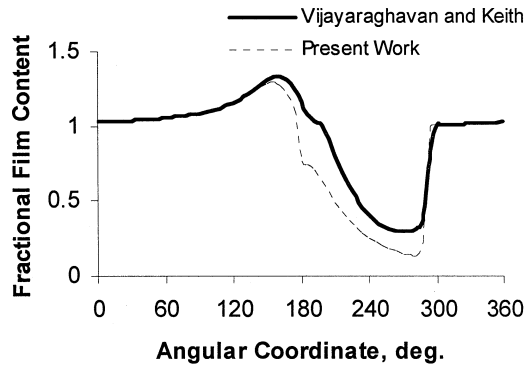
(a)



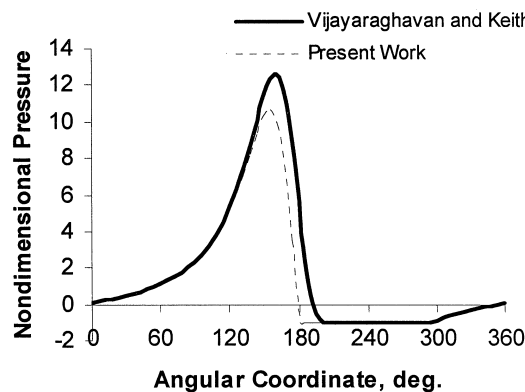
(b)

FIGURE 2

Results for a submerged journal bearing along the circumferential direction at the mid-plane of the bearing. $L/D = 4/3$ and $\varepsilon = 0.2$. (a) Fractional film distribution and (b) Pressure distribution.



(a)



(b)

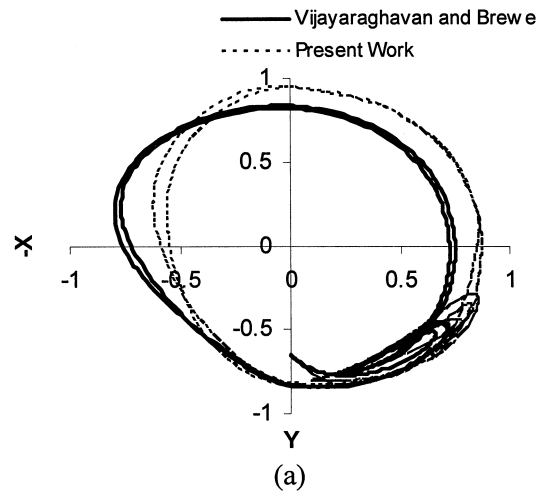
FIGURE 3

Results for a submerged journal bearing along the circumferential direction at the mid-plane of the bearing. $L/D = 4/3$ and $\varepsilon = 0.8$. (a) Fractional film distribution and (b) Pressure distribution.

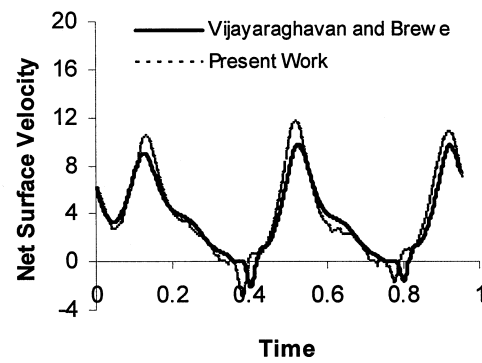
The axial ends of the bearing were at atmospheric pressure and the nondimensional cavitation gauge pressure is taken to be -1.0 . In the grid plane for the bearing, 6 and 61 nodes were considered in the axial and circumferential directions, respectively. Figures 2 and 3 show the nondimensional pressure distribution in a submerged journal bearing along the circumferential direction at the mid-plane of the bearing with $L/D = 4/3$, and $\varepsilon = 0.2$ and 0.8 , respectively. At $\varepsilon = 0.2$, the pressure profile using the present approach is close to that obtained using the Vijayaraghavan and Keith algorithm (Vijayaraghavan and Keith, 1989).

At the higher eccentricity ratios ($\varepsilon = 0.8$), the present method generates a lower peak pressure magnitude than the algorithm of Vijayaraghavan and Keith (1989). Also, at both $\varepsilon = 0.8$, the extent of cavitation boundary using the present work is greater compared to Elrod's striated flow model.

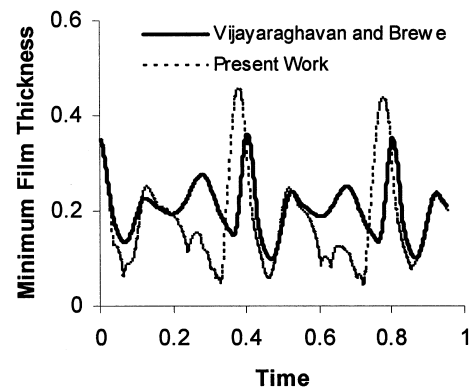
The journal transient analysis of a periodically loaded submerged journal bearing is obtained using the data analyzed by Vijayaraghavan and Brew e (1992). Results of transient analysis are obtained for journal trajectory, net surface velocity, and



(a)



(b)

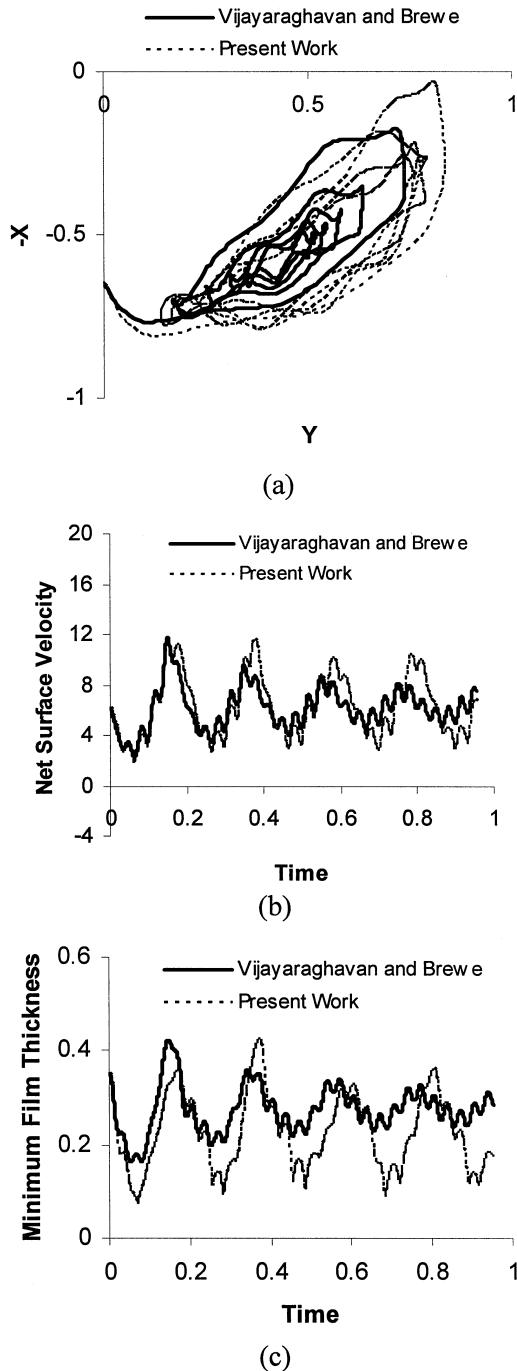


(c)

FIGURE 4

Results for the periodic loading in a submerged journal bearing. $\Omega = 0.25$. (a) Journal trajectory, (b) Net surface velocity, and (c) Minimum film thickness.

minimum film thickness at a frequency ratio (Ω) of 0.25 and 3.0 to determine the effect of varying frequency of periodic loading. In the axial direction, 5 nodes are considered for the grid plane, while in the circumferential direction 49 were considered. A nondimensional time step of 0.001 is used in the analysis.

**FIGURE 5**

Results for the periodic loading in a submerged journal bearing. $\Omega = 3.0$. (a) Journal trajectory, (b) Net surface velocity, and (c) Minimum film thickness.

Figures 4a, b, and c compare the journal trajectory, net surface velocity, and minimum film thickness predicted by both methods for $\Omega = 0.25$. Both methods predict that the journal attains limit cycle motion. The present cavitation model predicts a shift in the locus of the limit cycle journal motion (Figure 4a). The net

surface velocity becomes negative during the journal transient motion as predicted by both methods. However, higher peak values of net surface velocity are predicted using the present method (Figure 4b). The minimum film thickness predicted using the present method is lower than Elrod's cavitation model (Figure 4c). The transient journal response for frequency ratio $\Omega = 3.0$ is shown in Figures 5a, b, and c. The amplitude of the journal motion using the present approach is higher than when using Elrod's model (Elrod, 1981). There is no significant difference between the net surface velocities predicted by both methods (Figure 5b), however, the present method predicts a larger variation in the minimum film thickness (Figure 5c), as compared with Elrod's model based on striated flow (JFO) theory in the cavitation zone.

CONCLUSIONS

In a submerged journal bearing consisting of an enclosed cavity, it is assumed that a sublayer of thin lubricant film carried away by the journal surface shears the air cavity. The computational procedure presented herein is an extension of Elrod's universal equation based on the mass conservation principle considering striated flow. In the present approach, Elrod's universal equation is modified to incorporate the effect of shear of air cavity by the lubricant flow in the cavitation region. This model also assumes that the liquid film attached to the journal surface is transported in the cavitation region with a uniform velocity (non Couette flow) equal to that of the journal surface.

The main conclusions of the present study can be summarized as follows:

1. Under steady-state conditions (at an eccentricity ratio of 0.8), the maximum pressure obtained using the present method is lower than that predicted using the striated boundary conditions, while the cavitation boundaries predicted by the present model are larger than those predicted by Elrod's model utilizing striated flow.
2. For a periodic dynamic loading, the minimum film thickness obtained using the present model is lower as compared to those based on the application of Elrod's model.
3. For the Vijayaraghavan and Brew e's cavitation algorithm (based on Elrod's striated flow model), the variation of the minimum film thickness for the periodic loading at $\Omega = 3.0$ (Figure 5c) reduces over a period of time (i.e., the journal returns to equilibrium position), while using the present model, the minimum film thickness variation is constant for the given loading pattern and this indicates that the journal is executing a limit cycle motion. Hence, the stability threshold obtained using this study is lower than that compared to the striated flow model.

NOMENCLATURE

a_p	amplitude of periodic loading
C	radial clearance

D	journal diameter
f_i, F_i	bearing forces along vertical and horizontal directions, N; $F_i = \frac{f_i}{\eta\omega RL}(\frac{C}{R})^2, i = x, y$
h, H	oil film thickness, m; $H = h/C$
g	switch function
g_u	switch function for surface velocity
k	fluid velocity factor
K	bulk modulus, N/m ²
L	width of the bearing, m
m, M	rotor mass, kg; $M = \frac{mC\omega^2}{w}$
N	journal speed, rev/min
O_B, O_J	bearing and journal centers, respectively
p, P	oil film pressure, N/m ² ; $P = \frac{p}{\eta\omega}(\frac{C}{R})^2$
P_o	nondimensional steady state pressure for a finite bearing
P_j	nondimensional pressure gradients for finite bearing; $j = x, y, \dot{x}, \dot{y}$
R	journal radius, m
t	time, sec; $T = t\omega$
U	net surface velocity, m/s
w, W	applied load at any instant, N; $W = \frac{w}{\eta\omega RL}(\frac{C}{R})^2$
w_b	base load of periodic loading
x, X	vertical coordinate with respect to bearing center, m; $X = x/C$
y, Y	horizontal coordinate with respect to bearing center, m; $Y = y/C$
X, \dot{X}	nondimensional journal center displacement and velocity in x -direction
Y, \dot{Y}	nondimensional journal center displacement and velocity in y -direction
z, Z	coordinate along the axial direction, m; $Z = z/L$
α	angular coordinate measured from the vertical load direction
α_r	rupture (cavitation start) angle
α_m	reformation (cavitation end) angle
β	nondimensional bulk modulus, $\beta = \frac{K}{\eta\omega}(\frac{C}{R})^2$
ϕ	attitude angle
ρ	density of fluid, Kg/m ³
ρ_c	density of fluid at cavitation pressure, Kg/m ³
η_l	oil viscosity, Ns/m ²

η_g	air/oil solution viscosity, Ns/m ²
θ	nondimensional density fraction in full film (ρ/ρ_c), fractional film content in cavitation region
ω	journal angular velocity, rad/s
Ω	frequency ratio, ω_p/ω

Subscript

c	cavitation pressure
i	lubricant-cavity interface
o	pressures and forces calculated with reference to equilibrium position
s	saturation pressure
sup	supply pressure
l, g	liquid and air/gas cavity

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